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Semi-Annual Report  
Numerical and Symbolic Algorithms for  
Application Specific Signal Processing

April 5, 1994 – October 30, 1994

**Research Organization:** Digital Signal Processing Group  
Research Laboratory of Electronics  
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## 1 Introduction

During the period of this grant, our detailed technical accomplishments will be reported through journal articles and technical reports. Each of our semi-annual reports will highlight certain technical areas and provide a summary listing of our technical articles related to the project.

## 2 DSP System Design Tools

The first step in one aspect of our research in the RASSP program involves evaluating the abilities and limitations of current DSP system design tools. We are concerned with what algorithms the tools support, and how the tool abilities might be expanded in the future to support emerging signal processing techniques. This provides insight into how the RASSP process should be refined and expanded in order to make it useful to the designers of future signal processing systems.

To begin the evaluation, the use of tools in the design of a preprocessor for an avionic infrared system was examined. This led to the identification of several problems. The first was design re-entry. The algorithm was written and tested in MatLab, but there was no automated way to provide the algorithm description as input to a hardware synthesis tool. As a result, the design was manually re-entered into the synthesis tool. It was hoped that simulations in the synthesis tool could be compared with MatLab simulations to provide verification. This was not possible, however, because MatLab was performing computation with very high precision, while the synthesis tool was performing fixed point computation with a much shorter word-length. In addition, the simulation in the synthesis tool was much too slow to be practical (The processing time for one frame could be measured in days). In summary, the problems of design re-entry, MatLab's failure to compute bit-true results, and the slow simulation in the synthesis tool led to the inability to perform adequate verification, very late detection of errors, and significantly slowed development.

To avoid these problems, a design process should provide a "path to synthesis", i.e., a way to move smoothly from algorithm description to simulation to hardware synthesis, without manual re-entry of the design. The simulation environment should also provide the ability to specify the details of the computation at each stage in the algorithm. That is, the user ought to be able to specify the number of bits, the type of number representation

(two's-complement, floating point, etc.), and the manner of handling rounding and overflow issues. This "bit-true simulation" ability would be a great help in deciding how many bits to keep at each stage of the computation in order to maintain a sufficient signal-to-noise ratio.

Next, three commercial tools which address these issues in various ways were examined. It was found that they offer solutions to these problems only for a very limited set of problems. As the complexity of a signal processing system grows, or a system requires a type of processing which is not currently supported by the tool, the usefulness of the tool decreases rapidly.

With the abilities of several tools in focus, the support of other algorithms could be considered. It was found that multidimensional and multi-rate processing are two very important areas where support is much weaker than is needed for many designs. In particular, 2D FIR filter design and implementation is very awkward on the tools that provide bit-true simulation and/or a path to synthesis. Moreover, 2D IIR filter design and implementation is not supported by any commercial tools of which we are aware.

In our future work we plan to consider relationships among techniques in iterative processing, multidimensional processing, and the solution of partial difference equations. This could lead to finding new classes of algorithms and/or new applications for multidimensional filters. Note that this could have an impact on important applications like synthetic aperture RADAR and SONAR, geophysical processing, computed tomography, and biomedical ultrasound. We intend that this work could lead to making the RASSP process more useful by enabling it to support the design and implementation of a greater variety of signal processing systems.

### 3 Approximate Processing

Major accomplishments in our recent approximate processing research include: (1) conceptual and mathematical elaboration of approximate processing concepts [5], (2) formulation and implementation of a class of incremental refinement algorithms [4] for the short-time Fourier transform (STFT), (3) illustration of design issues in the context of incremental refinement algorithms [4], (4) continued development of the IPUS-C++ software environment [6] for supporting the design of application systems with embedded approximate signal processing capabilities, and (5) initiation of a project to build a software environment to support algorithm design for approximate signal processing. Although our investigations have so far focussed

mostly on the STFT, we have also initiated approximate processing research for wavelet transforms, wavelet packet transforms, high-resolution spectral estimators, and beamformers.

Our major results on approximate processing were presented [5] at the first annual RASSP conference held in Washington DC. In addition, we demonstrated the capabilities of our IPUS-C++ software environment during the exhibits portion of the conference. We refer you to our paper in the conference proceedings for a more detailed discussion of some of the results summarized below.

We have developed a mathematical framework for generating a space of possible algorithms for incremental STFT refinement. Each algorithm in this space implements a corresponding sequence of successive approximations. Each approximation in such a sequence can be quantitatively characterized in terms of the associated computational cost (we call this the cost increment) and the resulting improvement in STFT quality (we call this the quality increment) with respect to the previous approximation. In deriving this framework, each signal frame is assumed to be represented in 2's complement binary fraction format. The result of each successive approximation is controlled by a set of four positive integer-valued parameters. Increasing values of those parameters result in improved approximation quality. The value of each of those control parameters is required to never decrease across a sequence of successive approximations. This ensures that the corresponding algorithm is always refining the answer (as opposed to reducing its quality) as a function of time. Each successive approximation is implemented through a vector summation process we have previously reported [4,5] for similar approximations in the context of deadline-based algorithms. When all the successive approximations in a particular sequence are implemented this way, we refer to the implementation of the entire sequence as a single incremental-refinement algorithm. To sum up, we have devised a "generator equation" which forms the basis for generating many different sequences of successive STFT approximations and the corresponding incremental-refinement algorithms.

An important aspect of approximate processing algorithms is the systematic evaluation of their computational cost. For the space of algorithms represented by our generator equation the STFT approximations can be calculated using only additions. The number of additions required is signal dependent. However, we have formulated various means for calculating expected computational cost under a variety of signal assumptions.

We have also been investigating methods for finding algorithms from

among those corresponding to the generator equation that satisfy various types of constraints on their cost and quality increments. For example, we have developed methods [4] for designing incremental refinement algorithms with “uniform” incremental cost as well as with “exponentially decreasing” incremental cost. We have found that while some design questions can be answered analytically, in other cases it becomes necessary to use search and/or optimization procedures. Based on this insight, we have initiated the development of the design environment for approximate processing (DEAP). This environment will provide the numeric and symbolic processing capabilities that can support the design of approximate processing algorithms.

We are now adapting our IPUS-C++ software environment [6] to the task of designing application systems with embedded approximate signal processing capabilities. The IPUS-C++ environment enables rapid development of efficient signal understanding software systems in which numeric and symbolic signal processing may be integrated within a strategic and reactive control framework. This means, for example, that the system can initially produce an answer of low quality and then incrementally refine the answer until the higher level system goals are met.

## **4 Next-Generation Signal Processing Architectures**

An important component of the RASSP program involves exploring rich and promising next-generation signal processing architectures. Among these are potential networked architectures for distributed signal processing computation. These range from efficient parallel processing machines and other tightly-connected multiprocessor systems at one end of the spectrum, to more loosely connected networks of somewhat autonomous, stand-alone signal processing machines. As an example of the latter class, of increasing interest is the notion of constructing distributed signal processing systems out of processors, storage devices, and other resources linked via the internet or other public or private networks. In this application, the network serves as the backbone for the distributed signal processing system. In addition to their potential for use for distributed computation, networks such as the internet can also be used to share powerful, expensive, and computation-intensive design tools and other resources critical to the rapid prototyping of more traditional application-specific signal processors.

In exploring such uses of the internet and other packet-switched net-

works, it is important to adequately understand their data flow and error characteristics. Indeed, these characteristics give us critical insights into the kinds of constraints such links impose, and identify important areas for research in optimizing distributed signal processing systems subject to these inherent constraints. Traditional models for traffic on such networks have been based on the use of classical memoryless Poisson point processes. However, while these models have proven especially amenable to analysis, they have not tended to be especially realistic models for network behavior. Furthermore, traditional approaches to extending such models based on nonhomogeneous Poisson processes, while in principle rather general, are typically excessively mathematically cumbersome for these applications.

One component of our research program under RASSP has been exploring more realistic and useful models for network traffic, data flow, and error behavior. A particularly promising class of such models is based on the use of point processes with self-similar or fractal characteristics. Recent analyses of internet data has suggested that such models may be exceptionally well matched for these applications. More generally, these models have proven to be extremely well-suited to modeling a wide collection of natural and man-made phenomena. Other examples range from the distribution of stars and planets in the universe to the distribution of transmission errors in telephone networks to the auditory neuron firings in the ear.

However, despite their apparent applicability, the lack of an efficient, convenient, signal processing oriented framework for characterizing and representing self-similar point process models has severely limited their use in practice to date. Consequently, an important aspect of the initial phase of our work in this area has been on developing a suitable set of efficient mathematical tools for exploiting these models. As an important step forward in this direction, we have recently developed a novel and powerful multiscale framework for representing an important class of fractal point processes which we refer to as fractal renewal processes. Based entirely on Poisson constituents, this framework allows us to apply well-known results from the study of Poisson processes to a number of practical problems involving fractal renewal processes.

Fractal renewal processes are a class of fractal point processes with some important stationarity attributes, and are specifically well-matched to phenomena for which there is no natural notion of a time or space origin. In addition to being self-similar in the strict sense, a fractal renewal process is conditionally-renewing in that it behaves as a renewal process when observed over a window with finite resolution and finite size. A key property of

a fractal renewal process is that conditioned on such resolution and window-size limitation, the process has interarrivals distributed according to a power law probability density function. Furthermore, the exponent of this power law is linearly related to the fractal dimension of the point process.

Based on a multiscale approach, we develop a synthesis algorithm for fractal renewal processes which only requires a single prototype Poisson process. This representation involves a random mixture of a collection of constituents obtained by dilating or compressing the prototype process. The mixture is performed with an exponential random variable also derived from the prototype process. We show that when a continuum of constituents are employed, the synthesis can yield exact fractal renewal process behavior over an arbitrary finite range of scales. Good approximation of the fractal renewal process behavior can also be achieved with a discrete or finite collection of constituents. This discrete model is also extremely practicable.

In addition to its role in synthesis applications, our multiscale representation is also naturally suited to addressing several important practical estimation problems involving fractal point processes. Since the fractal dimension typically carries important information about a fractal point process, one problem of substantial interest is the estimation of this parameter. In our network modeling application, for example, this parameter provides a potentially useful measure of traffic density and other network state information. While traditional solutions to this parameter estimation problem have been limited to noise-free scenarios, using our framework we have been able to treat the more realistic scenario in which the measurements are corrupted by noise. In particular, using the Estimate-Maximize (EM) algorithm, we formulate an iterative procedure for obtaining the maximum-likelihood (ML) estimate of the fractal dimension based on corrupted measurements of the interarrivals. Consistency of the estimate thus obtained is established via Monte-Carlo simulations. Using the multiscale framework, we also develop an algorithm for obtaining Bayesian Least-Squares Estimates of interarrivals from corrupted measurements. This algorithm is directly applicable in the reconstruction of a fractal renewal process observed in a noisy environment. In our network modeling application, algorithms of this type may play an important role in measuring network activity and scheduling access. Theoretical error bounds for this algorithm is derived for assessment of its performance.

A more detailed discussion of our multiscale modeling algorithms is contained in [2]. The next phase of this work is aimed at specifically exploiting these new representations in modeling traffic on packet-switched networks



for distributed signal processing system applications.

## 5 Publications of Work Supported

K.M. Cuomo and A.V. Oppenheim, "Analysis, Synthesis, and Applications of Self-Synchronizing Chaotic Systems" to appear in *Nonlinear Dynamics in Circuits*, World Scientific Publishing, 1995.

K.M. Cuomo, "Synthesizing Self-Synchronizing Chaotic Arrays," *International Journal of Bifurcation and Chaos*, Vol. 4, No. 3, pp. 727-736, June 1994.

K.M. Cuomo, A.V. Oppenheim and S.H. Strogatz, "Robustness and Signal Recovery in a Synchronized Chaotic System," *International Journal of Bifurcation and Chaos*, Vol. 4, No. 6, pp. 1629-1638, December 1993.

S.H. Isabelle and G.W. Wornell, "Statistical Properties of One Dimensional Chaotic Signals," to appear in proceedings of the *International Conference on Acoustics, Speech and Signal Processing*, April 1995.

W.M. Lam and G.W. Wornell, "Multiscale Synthesis and Analysis of Fractal Renewal Processes," in *IEEE Proceedings of the Sixth Digital Signal Processing Workshop*, (Yosemite) CA, October 1994.

S.H. Nawab and J.M. Winograd, "An Incremental Refinement Approach to the Efficient Computation of DFT and STFT" to appear in proceedings of the *International Conference on Acoustics, Speech and Signal Processing*, April 1995.

A.C. Singer, G.W. Wornell and A.V. Oppenheim, "Nonlinear Autoregressive Modeling and Estimation in the Presence of Noise," *Digital Signal Processing*, Vol 4, pp 207-221, October 1994.

A.C. Singer, "Signal Processing with Nonlinear Wave Equations and Solitons," to appear in proceedings of the *International Conference on Acoustics, Speech and Signal Processing*, April 1995.

G.W. Wornell, "Efficient Symbol-Spreading Strategies for Wireless Communications," M.I.T. Research Laboratory of Electronics Technical Report 587, Cambridge, Massachusetts 02139, October 1994.

## 6 References

- [1] E. Dorken and S.H. Nawab, "Frame-Adaptive Techniques for Quality Versus Efficiency Tradeoffs in STFT Analysis," *Proc. IEEE Int. Conf. Acoust., Speech, Signal Processing*, (Adelaide) Australia, April, 1994.
- [2] W.M. Lam and G.W. Wornell, "Multiscale Synthesis and Analysis of Fractal Renewal Processes," in *IEEE Proceedings of the Sixth Digital Signal Processing Workshop*, (Yosemite) CA, October 1994.
- [3] S.H. Nawab and E. Dorken, "A Framework for Quality Versus Efficiency Tradeoffs in STFT Analysis," to appear *IEEE Trans. on Signal Processing*, Oct. 1993.
- [4] S.H. Nawab and J.M. Winograd, "Approximate Signal Processing Using Deadline Based and Incremental Refinement Algorithms," submitted to *ICASSP 95*.
- [5] A.V. Oppenheim, S.H. Nawab, G. Verghese and G. Wornell, "Algorithms for Signal Processing," *Proceedings of the First Annual RASSP Conference*, (Washington DC), August 15-19, 1994.
- [6] J.M. Winograd and S.H. Nawab, "A C++ Software environment for the Development of Embedded Signal Processing Systems," submitted to *ICASSP 95*.

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